The Influence of UHPFRC Jacket Steel Fiber Content on Strengthening Damaged Columns

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ABSTRACT

Steel fiber is a commonly used material to repair damaged concrete, caused by environmental or design issues. This study used various Micro-copper-coated Steel Fiber (MSF) content (0.0, 0.5, 2.0, and 2.5%) with varying aspect ratios (28, 37, and 45) as part of Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) mixtures to repair damaged concrete columns using a 30 mm layer jacketing. Twelve columns were prepared and tested at first by loading them with roughly 90% of their ultimate axial load capacity. Damage was caused and the columns were subsequently strengthened and rebuilt using UHPFRC mixtures in 30-mm layer jacketing for a second test, to determine the effect of UHPFRC and MSF content on damaged and reinforced columns. The test results showed that the concrete properties improved as the MSF content increased to 2.0% of the volume fraction, beyond which there was a slight reduction. Additionally, the UHPFRC-strengthened columns with and without MSFs experienced higher load capacities than the corresponding unstrengthened. On the contrary, using 2.5% MSF in the UHPFRC decreased the loading capacity by 14% compared to the UHPFRC with 2.0% MSF. The strengthened column with 2.0% MSF content showed the highest load efficiency (165.7% compared to unstrengthened), along with substantial displacement and ductility.

Keywords-aspect ratios; UHPFRC; load capacity; MSFs; jacketing

I. INTRODUCTION

Concrete is a widely used material in various sectors of the global construction industry. With its long-term durability, concrete structures can maintain their performance levels for several decades, provided they meet the safety requirements of the construction standards. However, Reinforced Concrete (RC) constructions are vulnerable to damage due to human design errors or environmental conditions such as fires, corrosion, and natural disasters [1]. Additionally, unintentional design flaws or alterations in buildings are considered the primary contributors to structural damage to beams, columns, and slabs, compromising their ability to support dead and live loads [1-2]. Among these components, columns are singularly responsible for bearing the entire vertical load to the soil. They are among the most crucial structural components and are frequently utilized in residential and high-rise buildings. Severe overload can cause significant column damage, causing deformation of the steel bars and potentially resulting in a surface fracture that could lead to a partial or complete structural collapse. Fractures on the concrete surface also expose vulnerable areas to corrosive agents, such as salt water and high humidity, which can penetrate and reach the steel reinforcement, ultimately leading to corrosion and reducing the load-bearing capacity of the concrete, leading to structural instability over time [3].

Ensuring a proper transfer of loads to the soil is crucial, making the repair and renovation of damaged building columns essential [4]. Repairing and reusing damaged concrete structures is often more cost-effective than demolishing and constructing new ones, although repairs can sometimes incur higher costs than new construction. However, while rehabilitation is a better alternative to demolition, it is considered one of the most challenging aspects of construction due to its inherent risks [5]. Before starting design and repair work, thorough examinations are imperative to accurately assess the condition to determine the appropriate repair materials and techniques to be used [1]. There are various solutions to rehabilitate overloaded and damaged reinforced concrete structures, with strengthening techniques being among the most commonly used for repairing damaged columns [6]. Depending on the severity of structural damage, several techniques can be applied, such as injections, removal, replacement, and jacketing.

Jacketing, in particular, finds frequent application in strengthening damaged RC columns, using three approaches: concrete jacketing, steel jacketing, and composite jacketing [2, 7]. Many studies have investigated the use of jackets made from Normal-Strength Concrete (NSC) and Ultra-High-Performance Fiber-Reinforced Self-compacting Concrete (UHPFRSC) to strengthen and repair columns. Compared to the unjacketed reference columns, the results show that both materials have better load-carrying capabilities and higher axial displacements. Moreover, RC columns can be repaired and strengthened using NSC as a jacketing material. However, UHPFRSC with steel fibers is more successful than others [1].

In [8], 37 specimens were examined at various eccentricities, ranging from e/t = 0 - 25%, and were divided into three groups: Group 1 comprised control columns with 5 specimens under various eccentricities, Group 2 used different amounts of steel wire mesh to reinforce 16 columns, and Group 3 used 16 specimens strengthened using a sandwich configuration of external vertical steel bars (3Ø8) on the compression side along with varying layers of steel wire mesh. All groups were coated with cement mortar. The results showed that the use of wire mesh jacketing increased the load-carrying capacity by up to 23% while using a sandwich wrapping system consisting of external vertical steel bars on the compression side and steel wire mesh increased capacity by up to 54%.

Composite jacketing is a contemporary approach that uses UHPFRC to extend the service life of RC structures at an affordable cost. UHPFRC can increase bearing capacity even in the presence of concrete cracks and significantly improve the structural longevity of structural concrete [1]. UHPFRC mixtures consist of steel fiber, water, superplasticizer (SP), Silica Fume (SF), cement, and sand, which collectively provide strength and ductility. UHPFRC improves concrete qualities such as toughness, ductility, and durability due to its uniformly dispersed fibers [9]. This technology has been developed to extend the service life of damaged RC structures by applying it to damaged areas for repair and subsequent reuse in building maintenance [10]. In [11], high-performance fiber-reinforced concrete jackets with a compressive strength of 170 MPa were used to strengthen short-column RC concrete. The results indicated that enhanced durability signifies progress in the concrete industry, yielding sustainable and economically viable buildings that are resistant to all types of corrosion. In [1], 25 and 35 mm thick jacketing was used to strengthen and repair damaged columns subjected to around 90% of their ultimate axial load capacities. This experimental study was conducted in two groups: Group 1 used regular-strength concrete with a maximum aggregate size of 4.75 mm and steel reinforcement, while Group 2 used UHPFRC with steel reinforcement. Group 2 exhibited significantly higher ultimate load capacity than Group 1 and the unjacketed reference column, with ratios of approximately three and 1.86 times, respectively.

It is imperative to identify cost-effective and time-efficient repair methods by exploring innovative approaches and materials. For example, the utilization of Micro-copper-coated Steel Fibers (MSF) with varying aspect ratios as internal reinforcement for repair mixtures remains relatively unexplored. This study aims to investigate the effect of MSF content in different aspect ratios (28, 37, and 45) within different UHPFRC mixture compositions (0.0, 0.5, 2.0, and 2.5%), using a uniform jacket thickness of 30 mm to repair square RC damaged by exceeded load capacity. The columns were subjected to axial compression loads until failure. Load capacity, displacement, ductility, and failure modes were recorded, observed, and subsequently compared.

II. MATERIALS AND METHODS

This study investigated the effects of UHPFRC using MSF with a range of varying contents and aspect ratios as repair materials to strengthen and rehabilitate damaged columns subjected to overload. The columns were bonded on all four sides and jacketed with a fixed thickness of 30 mm. Figure 1 shows the framework of the experimental study.

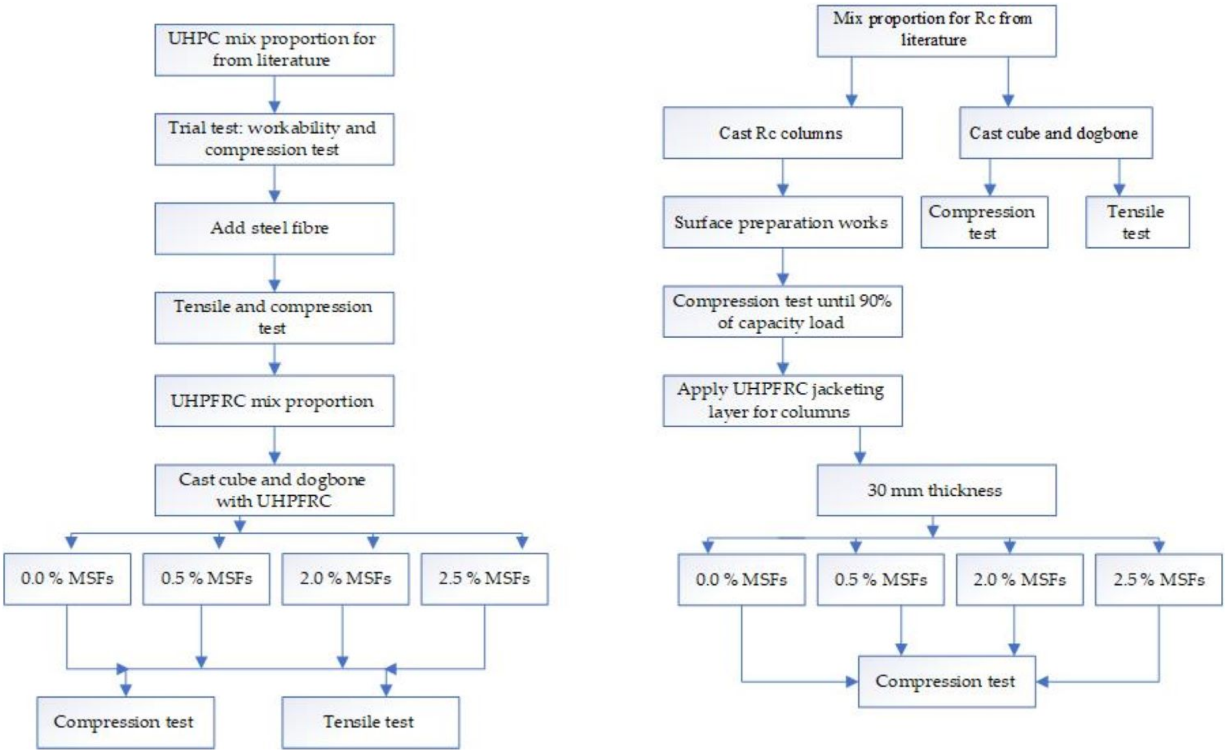

Fig. 1. The experimental research method.

A. Materials

MSF, as shown in Figure 2, and SF, as shown in Figure 3, were obtained from Shandong Federal Fibre Co., Ltd. and Fosam Company Ltd., respectively. The MSF had various aspect ratios, with three different lengths of straight fibers (10-16 mm) and a fixed diameter of 0.35 mm, as shown in Table I. According to the supplier's datasheet, the SF had a strength of 7900 MPa and a specific gravity of 7.9. Sodium Naphthalene Sulfonate (SNF) was supplied by a local Saudi Arabian company to improve the durability and service life of concrete, by improving the strength of the mixture by 20-60% [12]. SP conplast SP430 was used with a specific gravity of 1.06 to improve the workability of the concrete mixture. All prepared concrete mixtures were cast using Type 1 Ordinary Portland Cement (OPC), featuring an initial settling time of more than 45 minutes. Columns were reinforced using steel bars with a diameter of 12 mm diameter, 460 MPa yield strength, 610 MPa ultimate strength, and Young's modulus of 200 GPa was obtained experimentally.

TABLE I. MSFS PROPERTIES

Fiber Properties	MSFs	MSFs	MSFs
Shape	Straight	Straight	Straight
Length (mm)	10	13	16
Diameter (mm)	0.35	0.35	0.35
Aspect ratio	28	37	45
Tensile strength, (MPa)	2800	2800	2800
Young modulus (GPa)	200 GPa	200 GPa	200 GPa
Specific gravity	7.9	7.9	7.9

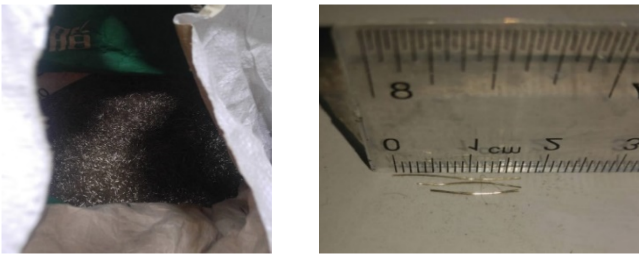
(a) (b)

Fig. 2. (a) MSF, (b) MSF of different lengths.

Fig. 3. Silica fume.

B. Column Preparations and Details

Twelve square column specimens were fabricated, each designed to adhere to a minimum longitudinal reinforcement ratio of 1% [13]. These columns acted as standard columns when subjected to overloading, subsequently undergoing repair and reinforcement through UHPFRC jacketing. The columns had cross-sectional dimensions of 150×150 mm and a height of 500 mm, featuring 4Ø12 mm longitudinal steel reinforcement and 6Ø8 mm link bars spaced at 75 mm center-to-center, as shown in Figure 4.

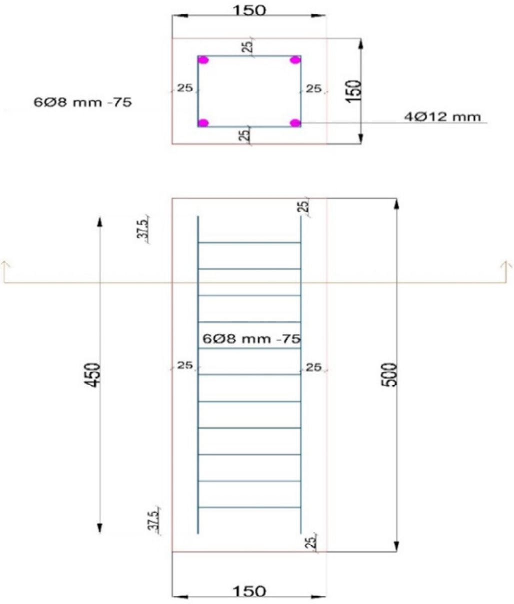

Fig. 4. Reinforcement column details.

C. Mix Design for Columns

The concrete mixes consisted of 745 kg/m^3 sand, 805 kg/m^3 coarse aggregates (size 10-14 mm), 250 kg/m^3 water, and 550 kg/m^3 OPC [14]. The concrete mixture featured sand with a relative density of 3.15, a fineness modulus of 3.4, and an absorption rate of 1%. It also incorporated natural crushed coarse aggregate with a maximum size of 14 mm and Type 1 OPC. The mix proportion was formulated to achieve a target compressive strength of 30 MPa in 28 days [13]. The mixes were used to cast columns, cubes, and dogbone specimens. The 12 square columns, along with 100 mm cube edges and dogbone samples, were cured in water for 28 days and subsequently exposed to room temperature until testing.

D. Test Setup and Column Instrumentation before Repair

Axial compression loads were applied to the columns using a hydraulic Universal Testing Machine (UTM) with a capacity of 200 tons. Steel plates were affixed to the upper and lower surfaces of each column to evenly distribute the axial load across the column. Before testing, the top surface was polished using a Gipson layer. A total of 12 RC columns were subjected to concentric axial compression loads at approximately 90% of their actual axial capacities, as shown in Figure 5, with a displacement rate of 0.5 mm/min until hairline cracks emerged, without reaching failure states. Among the 12 unrepaired columns, three exhibited the most promising values and were selected as control samples. Data were recorded through a computer system connected to the testing machine.

E. Test Setup and Column Instrumentation after Repair

Based on the data shown in Table II, the columns were sorted into four groups of MSF content: 0, 0.5, 2.0, and 2.5%. The addition of SNF to the mixture helped increase its strength from 20% to 60% [15]. Due to the influence of UHPFRC rheology, SF was limited to 6% of the content since when it exceeds a particular threshold (>10%), UHPFRC loses compression strength [16]. MSFs were added to the mix with varying contents of 0, 0.5, 2.0, and 2.5% and various aspect ratios of 28, 37, and 45, respectively, to enhance concrete properties. UHPFRC was used to reconstruct all the damaged columns using 30 mm thick jacket layers, as shown in Figure 6. To further monitor the compression strength of concrete in each mixture, concrete cubes and dogbone-shaped specimens were taken from the reinforced and repaired compositions.

TABLE II. MIXTURE PROPORTION FOR UHPFRC FOR 1 M³.

ID	Fiber (%)	W/C (-)	SNF (kg)	Sand (kg)	SP430 (kg)	SF (kg)	MSF (kg)	Water (kg)	Cement (kg)
M1	0.0	0.25	5	887	55	53	0.0	250	1000
M2	0.5	0.25	10	887	65	53	39.5	250	1000
M3	2.0	0.25	10	887	65	53	158	250	1000
M4	2.5	0.25	10	887	65	53	197.5	250	1000

Fig. 5. Testing of concrete columns until 90% load compression damage.

Fig. 6. Casting a square column with repaired material.

Based on the test variables shown in Table III, the columns were sorted into five groups. The first group (Co 0) was prepared from the normal concrete mix (M 0) and the three best of the 12 unrepaired columns were chosen as control specimens. In the second group (Co 1), three columns were strengthened with MSF-free UHPRC jacketing to study its effect on column behavior. In the rest of the groups (Co 2, Co 3, and Co 4), three columns in each group were strengthened by UHPFRC jacketing with MSF content of 0.5, 2.0, and 2.5% to study its effect on columns' behavior. All mixed groups were used to cast the column damage and the 100-mm cube. Columns and cubes were cured in water for 28 days and then kept in air at room temperature until the test day. All repaired specimens with UHPFRC were tested under axial compression with a displacement rate of 1 mm/min, as recommended in [17], until cracks appeared and the specimens failed, as shown in Figure 7. The average of the three-column specimens was considered during the loading process. Axial load and vertical displacement data were recorded through a computer system connected to the machine, and then the vertical load-displacement curve was plotted, which led to the determination of the ultimate load, displacement, and ductility. The crack patterns and the failure modes were determined throughout the experiment.

TABLE III. COLUMNS' DETAILS AND TEST VARIABLES

Group ID	Column ID	Concrete mix	Strengthening layer	Test variables
Co 0	Co 01	M0	None	The best value without strengthening
	Co 02			
	Co 03			
Co 1	Co 11	M1	0.0 % MSFs	Jacketing strengthening
	Co 12			
	Co 13			
Co 2	Co 21	M2	0.5 % MSFs	Content of MSF jacketing strengthening
	Co 22			
	Co 23			
Co 3	Co 31	M3	2.0 % MSFs	
	Co 32			
	Co 33			
Co 4	Co 41	M4	2.5% MSFs	
	Co 42			
	Co 43			

Fig. 7. Testing of concrete column damage after using the repaired material.

III. TEST RESULTS

A. Concrete Properties

Table IV summarizes the properties of concrete mixes with and without UHPFRC jacketing. Compressive strength was obtained by testing three standard test cubes (100×100×100 mm) at the end of 28 days. The increase in MSF content in repair concrete also led to increased tensile and compressive strengths (f_{tu} and f_{cu}). At the testing date, after 28 days from casting, the f_{tu} and f_{cu} of M 0 for reinforcement concrete were 37.3 MPa and 2.41 Mpa, respectively. Since the MSF content included in the UHPFRC was 0, 0.5, 2.0, and 2.5%, the compressive strength increased by 147.7, 169.1, 218.49, and 193.03%, respectively. These results corroborate previous studies [18-21]. However, compressive strength was observed to increase with MSF content of 0.5-2.0%, while it slightly decreased when using more than 2%. Therefore, the addition of MSF only to a certain extent increases the compressive strength [22]. In contrast, tensile strength is considered the most important feature of UHPFRC because the tensile strength in a cementitious repair material is important to avoid or reduce shrinkage deformations at an early stage. In this study, dogbone-shaped specimens were used to obtain tensile strength by testing all the mixtures at 28 days, as shown in Figure 8. Table IV shows that tensile strength increased by 125.9, 142.3, 190.80, and 202.7%, which was higher than the increase in compressive strength, while this increase might help close concrete cracks [23-25]. In [26], it was reported that using 1% or less steel fibers enhanced the properties of the concrete in general.

TABLE IV. COMPRESSIVE AND TENSILE STRENGTH OF CONCRETE WITH AND WITHOUT JACKETING

Mix ID	MSF (%)	f_{cu} (MPa)	μ_{cu} (%)	f_{tu} (MPa)	μ_{tu} (%)
M 0	0	37.3	-	3.59	-
M 1	0	55.1	147.7	4.52	125.9
M 2	0.5	63.1	169.1	5.11	142.3
M 3	2.0	81.5	218.49	6.85	190.80
M 4	2.5	72	193.03	7.28	202.7

f_{cu}= compressive strength, f_{tu}= tensile strength, μ_{cu}= ratio of compressive strength of any mix and mix 0, μ_{tu}= ratio of tensile strength

B. *Load Capacity and Failure Mode of Columns*

Table V shows the experimental results of the columns tested in terms of maximum load (P_u), failure modes, and displacement. The loading efficiency of the columns without strengthening by jacketing was calculated from:

$$(\mu_{u\ averge} = \frac{P_{u,str\ averge.}}{P_{u,Cc\ averge}}) \qquad (1)$$

In general, all jacketed columns showed higher maximum load capacities than the unstrengthened (Co 0). The Co 3 group, which had 2.0% MSF, showed the highest load capacity, since it increased by 165.7% compared to the unstrengthened columns (Co 0). According to [27], an increase in the volume of polyethylene fibers from 1% to 2% led to an increase in the maximum compressive load. Table V shows that the columns strengthened without MSF showed lower load capacities. Jacketing with 2.5% MSF had a trivial 15.9% decrease in column capacity compared to the column jacketed with 2% MSF. This shows that increasing the steel fiber by more than 2.0% of the volume will less effectively hold the microcracks in concrete and, consequently, have less loading capacity [22].

Fig. 8. Experimental tensile test of dogbones.

In terms of failure mode, unstrengthened specimens cast with normal concrete (Co 0) were crushed (CC), as shown in Figure 9(a). In general, Figure 9(b)-(e) shows that the failure modes of the strengthened columns by UHPFRC jacketing showed concrete crushing (CC) followed by Steel Buckling (SB). On the contrary, including MSF at 0.5%, 2.0%, and 2.5% content, the failure pattern improved due to the increased load capacity of the specimens compared to the corresponding column cast with M 0. Figure 9(d) shows that the use of 2.0% instead of 2.5% MSF had a trivial effect on the maximum column load by creating smaller cracks, as the column failed on the strengthened portion. The reason may be that the effect of increasing the MSF was limited to a certain percentage, which would be less useful when exceeded.

TABLE V. CONCRETE PROPERTIES AND COLUMNS EXPERIMENTAL RESULTS.

Group ID	Column ID	f_{cu} (Mpa)	$\mu 1$ (%)	f_{tu} (Mpa)	$\mu 2$ (%)	P_u (kN)	average P_u (kN)	average μ_u (%)	Failure modes
Co 0	Co 01	37.3	-	3.59	-	472.0	446.6	-	Crushing (CC)
	Co 02					453.0			
	Co 03					415.0			
Co 1	Co 11	55.1	147.7	4.52	125.9	490.4	506.5	113.4	Crushing (CC) and Buckling (SB)
	Co 12					498.6			
	Co 13					530.6			
Co 2	Co 21	63.1	169.1	5.11	142.3	599.0	616.8	138.0	
	Co 22					643.4			
	Co 23					608.0			
Co 3	Co 31	81.5	218.49	6.85	190.8	767.9	740.3	165.7	
	Co 32					747.4			
	Co 33					706.5			
Co 4	Co 41	72.0	193.03	7.28	202.7	660.6	669.0	149.8	
	Co 42					657.7			
	Co 43					688.8			

(a) Co 0 (b) Co 1 (c) Co 2 (d) Co 3 (e) Co 4

Fig. 9. Failure modes of the tested columns.

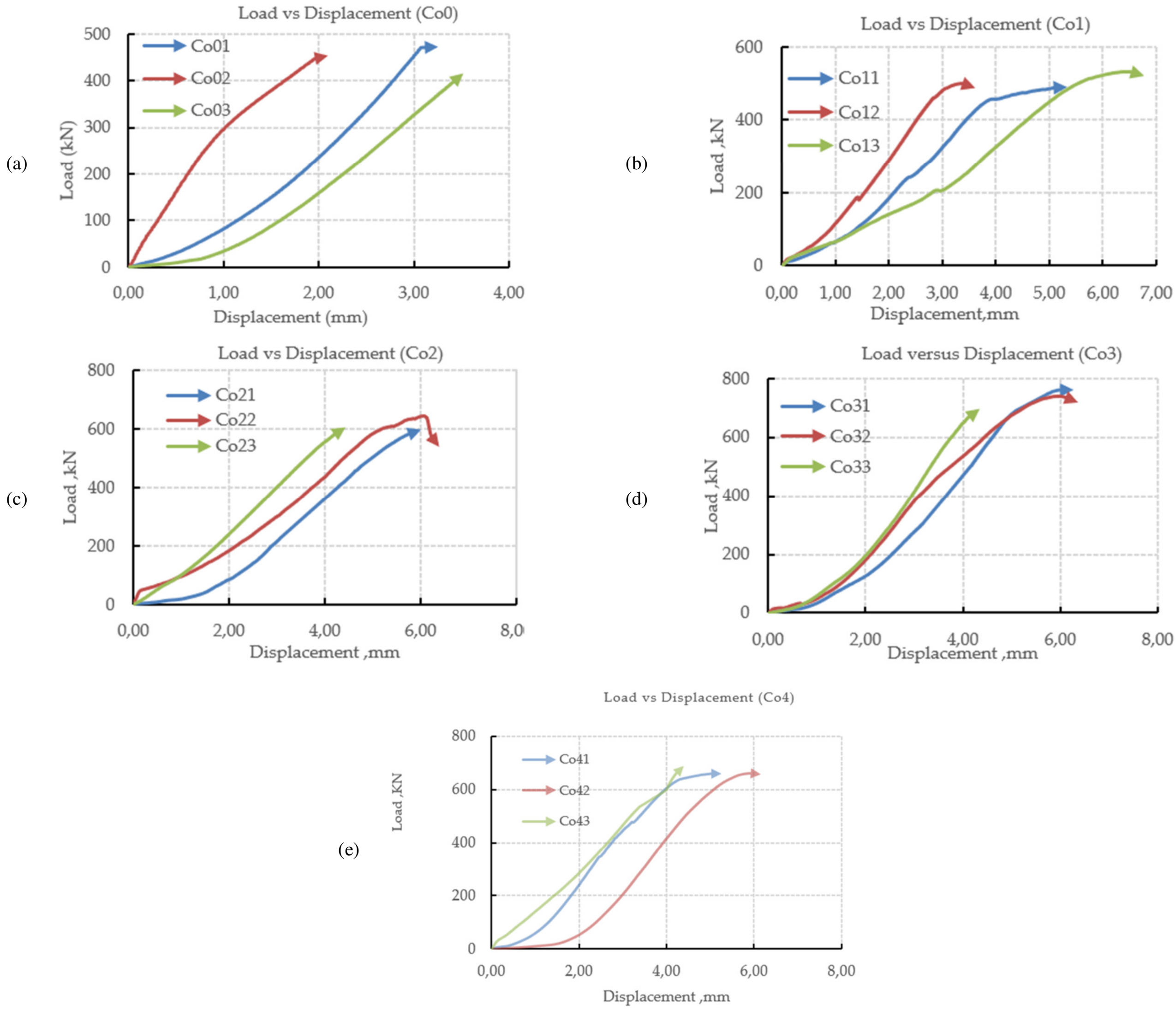

Fig. 10. Load-displacement curves of the tested columns: (a) M0, (b) M1, (c) M2, (d) M3, and (e) M4.

C. *Load-Displacement and Ductility Behavior*

Figure 10 shows the experimental load-displacement behavior of the tested columns. Figure 10(a) shows that the M1 jacketed columns showed higher initial displacements, averaging up to 72.41% of the Co 0 column's displacement. Table VI shows that the displacement and ductility of the columns strengthened with UHPFRC jackets surpassed those of Co 0 from initial loading until failure. This can be attributed to the UHPFRC jacketing layer, which temporarily constrained and delayed lateral deformation. Moreover, MSF increased the displacement and ductility of the column, regardless of the MSF content, as shown in Figures 10(b-e). This means that it improved the column's stiffness until its maximum load and increased its ductility until the maximum load reached failure. The three columns strengthened by UHPFRC jacketing with 2.0% MSF (Co 31, Co 32, and Co 33), showed higher stiffness through increased displacement compared to all the other strengthened columns. This could be because the increase in MSF content led to increased lateral deformation and column ductility [28]. Therefore, repairing with UHPFRC would restore the load-bearing capacity of concrete [29]. On the contrary, Table VI shows that Co 4 showed a lower average displacement and ductility than Co 3 by 7.54% and 4.16%, respectively, despite the increase in MSF. This could be because increasing the steel fiber content by more than 2.0% of the volume will be less effective in decreasing lateral deformation and helping to arrest the column cracking.

TABLE VI. LOAD-DISPLACEMENT AND DUCTILITY COLUMNS EXPERIMENTAL RESULTS

Group ID	**Column ID**	***Pu* (kN)**	**Average Pu (kN)**	**Δ*yield* (mm)**	**Average Δ*yield* (mm)**	**Δ*ult* (mm)**	**Average Δ*ult* (mm)**	**Ductility index *µ***	**Average Ductility Index *µ***
Co 0	Co 01	472.0	446.6	2.90	2.67	3.1	2.9	1.07	1.10
	Co 02	453.0		1.80		2.1		1.17	
	Co 03	415.0		3.32		3.5		1.06	
Co 1	Co 11	490.4	506.5	4.39	4.32	5.2	5.0	1.20	1.16
	Co 12	498.6		3.10		3.4		1.11	
	Co 13	530.6		5.47		6.5		1.18	
Co 2	Co 21	599.0	616.8	5.72	4.73	5.72	5.1	1.05	1.17
	Co 22	643.4		4.80		4.80		1.26	
	Co 23	608.0		3.67		3.67		1.21	
Co 3	Co 31	767.9	740.3	4.82	4.60	6.3	5.7	1.32	1.25
	Co 32	747.4		4.53		6.1		1.35	
	Co 33	706.5		4.45		4.7		1.10	
Co 4	Co 41	660.6	669.0	4.17	4.36	5.2	5.3	1.26	1.20
	Co 42	657.7		4.92		6.1		1.25	
	Co 43	688.8		3.99		4.3		1.10	

IV. CONCLUSION

This study investigated 12 damaged reinforced concrete columns rehabilitated with a UHPFRC jacketing layer at different MSF content under axial compression loads, drawing the following conclusions:

- The use of UHPFRC led to enhanced concrete properties, notably increased compressive and tensile strengths, surpassing those of traditional RC, and was consistent with previous studies.
- All columns strengthened through UHPFRC jacketing, either with or without MSFs, showed higher maximum load capacities of up to 65.76% compared to unstrengthened columns.
- The use of MSF in the UHPFRC mixture to repair damaged columns resulted in improved concrete properties and increased column capacity. An optimal steel fiber content threshold of around 2.0% volume fraction was shown to achieve the maximum load-bearing capacity of the column, conforming with previous works mentioning that 2% is the ideal steel fiber content in concrete.
- Columns strengthened by jacketing with 2.0% MSF UHPFRC showed higher stiffness, load capacity, displacement, and ductility in comparison to the unstrengthened and the other strengthened columns. Furthermore, all jacketing layers (30 mm) increased column capacities and stiffness to the point of maximum loads, subsequently improving column ductility.

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